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The Neutron star Interior Composition Explorer (NICER): mission definition

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ABSTRACT

Over a 10-month period during 2013 and early 2014, development of the Neutron star Interior Composition Explorer (NICER) mission [1] proceeded through Phase B, *Mission Definition*. An external attached payload on the International Space Station (ISS), NICER is scheduled to launch in 2016 for an 18-month baseline mission. Its prime scientific focus is an in-depth investigation of neutron stars—objects that compress up to two Solar masses into a volume the size of a city—accomplished through observations in 0.2–12 keV X-rays, the electromagnetic band into which the stars radiate significant fractions of their thermal, magnetic, and rotational energy stores. Additionally, NICER enables the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) demonstration of spacecraft navigation using pulsars as beacons. During Phase B, substantive refinements were made to the mission-level requirements, concept of operations, and payload and instrument design. Fabrication and testing of engineering-model components improved the fidelity of the anticipated scientific performance of NICER's X-ray Timing Instrument (XTI), as well as of the payload's pointing system, which enables tracking of science targets from the ISS platform. We briefly summarize advances in the mission's formulation that, together with strong programmatic performance in project management, culminated in NICER's confirmation by NASA into Phase C, *Design and Development*, in March 2014.

Keywords: X-ray, neutron star, pulsar, timing, SEXTANT, XNAV, navigation, International Space Station

1. INTRODUCTION

To address long-standing and widely recognized astrophysical research objectives, NASA's Neutron star Interior Composition Explorer (NICER) Mission of Opportunity promises a comprehensive understanding of neutron stars, exotic objects that embody a physical environment impossible to reproduce in any laboratory, one in which all four fundamental forces of nature are simultaneously important. Through time-resolved spectroscopy in soft (0.2–12 keV) X-rays, NICER offers an exploration of the interior structure of neutron stars, the highly time-variable phenomena that they manifest, and the energetic emissions of their powerful magnetospheres. NASA's Goddard Space Flight Center (GSFC) provides scientific and engineering leadership for the development of NICER, in collaboration with MIT's Kavli Institute and industry partners. NICER's X-ray Timing Instrument (XTI)—an array of 56 co-aligned X-ray "concentrator" optics with associated silicon-drift detectors—offers high throughput with low susceptibility to radiation background, while its modular design mitigates risk. A GPS receiver provides the position and time reference needed to coherently time-tag photon detections, enabling X-ray photometry and spectroscopy with unprecedented time resolution and sensitivity. NICER also makes possible a first-of-its-kind technology demonstration: real-time, on-board orbit determination using NICER's key science targets, millisecond-period pulsars, as celestial navigation beacons. With its innovative X-ray timing capabilities, NICER is poised to answer fundamental questions about nuclear physics and neutron star astrophysics, while enabling future exploration by advancing pulsar-based spacecraft navigation.

As described in [1], NICER probes interior composition of neutron stars through stellar radius and mass measurements. Typically, these are derived respectively from high-quality lightcurves (the modulation of X-ray brightness as the star rotates, influenced by relativistic light-bending and Doppler shifts) and from relativistic modifications to the observed

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pulse times-of-arrival from neutron stars in binary systems. NICER carries out rotation-resolved spectroscopy of the most rapidly spinning neutron stars, enabling lightcurve analysis (e.g., [2,3]) with unique power to resolve competing stellar models. The anticipated science outcomes are discrimination among families of proposed models for the neutron star equation of state (EOS) and unique constraints on basic unknowns of nuclear physics, such as the incompressibility of bulk nuclear matter, the three-body interaction potential, and the density-dependent nuclear symmetry energy.

NICER also investigates time-variable phenomena responsible for the dynamic behavior observed from neutron star systems, from uncovering the basic spin rates of newly discovered objects and characterizing variations in spin (due to interior and exterior processes), to inferring the timescales over which neutron stars cool following their fiery birth. The anticipated science outcomes are follow-up pulse timing to enable mass and radius measurements; constraints on the maximum spin rate of neutron stars; long-term clock stabilities that support Pulsar Timing Array gravitational-wave searches (e.g., [4]); and a new window of discovery into neutron star seismology.

Finally, NICER probes magnetospheric particle acceleration and radiation processes, through rotation phase-dependent spectroscopy. Anticipated science outcomes are valuable new tests of radiation models in ultra-strong magnetic and gravitational fields.

These measurements require high-precision, absolute timing with a combination of effective collecting area and mission-aggregate exposure time that together enable unprecedented signal-to-noise ratios in accumulated lightcurves, with appropriate spectral coverage and resolution. Targets identified for the baseline science program have been selected because they most readily enable these science investigations by virtue of their known, relevant properties such as brightness, spin period, timing stability, magnetic field strength, etc. Additional, currently unknown, targets will be available to NICER as a result of continuing searches for neutron stars, especially at radio and γ-ray wavelengths and with NICER itself.

2. MISSION REQUIREMENTS

Achievement of NICER's science objectives in neutron star structure, dynamics, and energetics imposes a set of measurement and design requirements that ensure successful implementation of the mission. Their scope includes all mission lifecycle phases and drives design considerations for the payload (including its accommodation on the ISS and at launch), the mission operations center, and science operations.

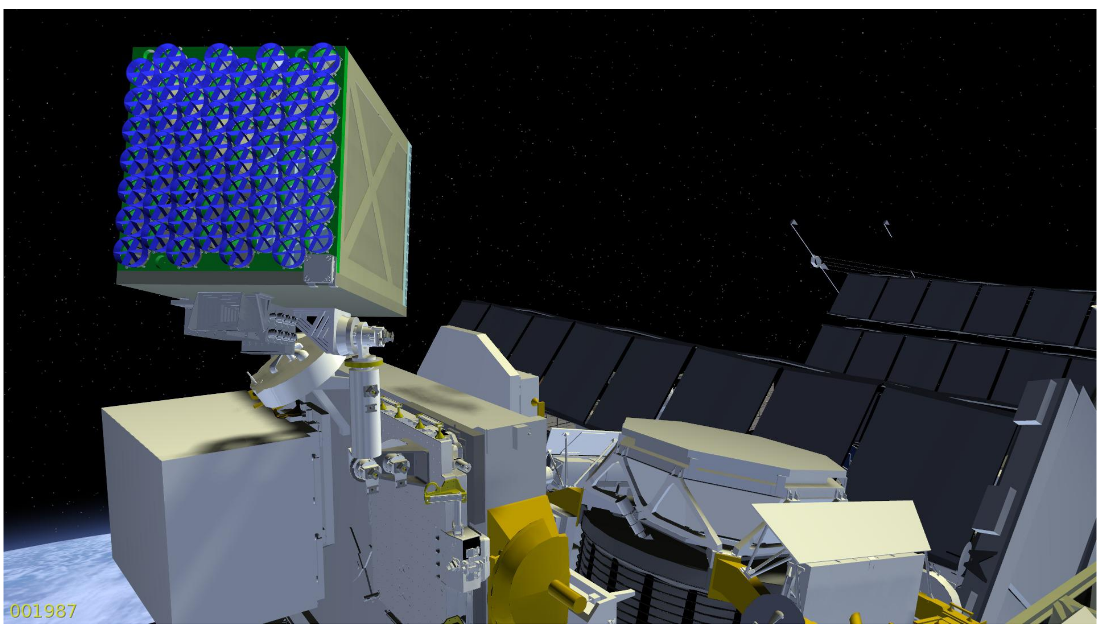

Figure 1. The NICER payload, with sunshades depicted in blue in this illustration, is shown deployed atop the Pointing and Deploy System (DAPS) boom. At its lower end, the boom is attached to a standard Flight Releasable Attachment Mechanism (FRAM), which in turn is attached to the S3 ExPRESS Logistic Carrier on the ISS.

The NICER mission consists of two primary segments: flight and ground. The flight segment includes the NICER payload and its host (Figure 1); the latter locates the payload on a zenith-side ISS ExPRESS Logistics Carrier (ELC). The ELC is required to provide structural support, power, uplink commanding capability from the ground, and data handling, storage, and downlink. The ground segment comprises both NASA institutional infrastructure and mission-specific elements. The Payload Operations Integration Center (POIC) at NASA's MSFC provides the communications link from the ground to the payload via the Space Station Control Center at NASA's JSC and the Space Network. The Science and Mission Operations Center (SMOC) at NASA's GSFC, as the NICER control center, provides payload commanding and monitoring as well as all data handling including capture, processing, storage, and data product distribution to the NICER repository at the High Energy Astrophysics Science Archive Research Center (HEASARC).

2.1 Baseline science requirements

NICER's top-level science requirements call for making radius and mass measurements at the 5–10% level for at least three neutron stars; determining the X-ray flux modulation properties of at least 20 candidate pulsars; characterizing spin variations and outbursts (such as during pulsar "glitches"); establishing the intrinsic rotational stabilities of millisecond pulsars on months-to-years timescales; and determining the absolute rotational phases of particle acceleration and radiation regions in neutron star magnetospheres.

Such measurements are made possible by specifying a set of technical performance requirements that together drive the instrument and mission design. NICER is required to:

- Measure energy-dependent X-ray lightcurve shapes, accumulating sufficient photons (typically, $10^{5–6}$) to achieve 5% radius measurements
- Measure Shapiro delays as small as 50 μs in magnitude, for pulsars in appropriate binary systems (e.g., inclination ≥ 80º and/or companion mass ≥ 0.5 $M_{\odot}$)
- Search for periodic and quasi-periodic pulsations on millisecond and sub-millisecond timescales to a limiting 0.5–10 keV flux of 1×10^{-14} erg/cm^2/sec
- Measure pulse arrival times to ≤ 1 μs RMS at least once a month over at least 18 months, with gaps of no longer than 3 months
- Distinguish spectrally between thermal and nonthermal X-ray pulse spectra, and measure their absolute phases to 100 μs accuracy.

2.2 Design rationale and selected lower-level requirements

High-level science requirements drive the essential capabilities of a mission. NICER's implementation of its required capabilities additionally takes into consideration the opportunity presented by the ISS to carry out full mission science at lower risk and cost as a Mission of Opportunity payload. A summary of the NICER design rationale follows, with references to selected lower-level requirements adopted by the NICER project.

NICER's highest-priority science derives from analysis of thermal X-ray pulsation lightcurves for a handful of targets distributed across the sky. Simulations (see [1]) demonstrate that, depending on details of the lightcurve shape, collection of $10^{5–6}$ photons is needed from each target; this may be achieved through a suitable balance of effective collecting area and exposure time. Thermal emissions from rotation-powered pulsars peak at energies well below 1 keV, so that the capability to detect photons with energies as low as 0.2 keV is required. In this soft band, the diffuse glow of cosmic background X-rays becomes important over areas of sky greater than a few tens of arcmin^2. A narrow field-of-view (FOV) instrument, that need not have imaging capability, is therefore required—the size of NICER's FOV, 28 arcmin^2, is driven by sensitivity considerations for lightcurve modeling and for searches for previously unknown pulsations. The size of the FOV governs, in turn, the performance of the optical system that collects the X-rays, the capability of the mechanism that points the instrument, and the operation plan for achieving the required deep exposures. NICER's pointing system, for example, is required to maintain the instrument observing axis to within 66 arcsec of the target while its mechanical alignment budget ensures optic/detector boresights remain within 54 arcsec of the observing axis.

For a one-year threshold mission and a conservatively assumed operational efficiency of 33%, sufficient time (10 Msec = one-third of a year) exists to accumulate the needed numbers of photons for lightcurve modeling of three neutron stars—and to complete the remainder of the threshold mission—with total exposures ≤ 1.5 Msec each. The minimum required peak effective collecting area is then $A_{eff} \geq 1333$ cm^2 for objects, similar to PSR J0437–4715, with photon flux

≥ 0.5 cts/ksec/cm^2 (corresponding to a 0.2–2 keV energy flux of approximately 1×10^{-13} erg/s/cm^2 for a 1 MK blackbody with neutral hydrogen absorbing column of 10^{21} cm^{-2}). Thus, to accommodate the instrument-level peak Aeff requirement, the X-ray collection system must provide a geometric collecting area ≥ 4000 cm^2 with efficiency ≥ 48% for 1.5 keV X-rays throughout the mission life. NICER's grazing-incidence foil concentrators, with appropriate thermal filters in the optical path, fulfill this requirement (Figure 2). The geometric collecting area is accommodated within the volume envelope of an ISS ELC payload, which also imposes a maximum focal length; together, the focal length and collecting area determine the modularity of the NICER instrument (56 concentrator/detector pairs) through X-ray reflectivity considerations: at a graze angle of 1.35°, the outermost concentrator foils provide 82% reflectivity at 0.2 keV but less than 0.1% at 10 keV. Finally, an overall collection efficiency requirement, including detector properties, is satisfied: to enable the instrument-level peak A_{eff} requirement, the X-ray detection system must provide a quantum efficiency at 1.5 keV of ≥ 67% throughout the mission life. At the detector, low-energy efficiency is realized through the choice of a suitably thin thermal and optical-blocking filter, while the high-energy requirement is met with an appropriately thick detector. The detector's energy resolution requirement (100 eV FWHM below 1 keV; 200 eV between 1 keV and 10 keV) is satisfied with a cooled silicon device. Mitigation of additional sources of background in orbit—particle and penetrating electromagnetic radiation—requires a combination of veto capability (e.g., pulse-height and rise-time discrimination) and that the X-ray detectors are physically compact.

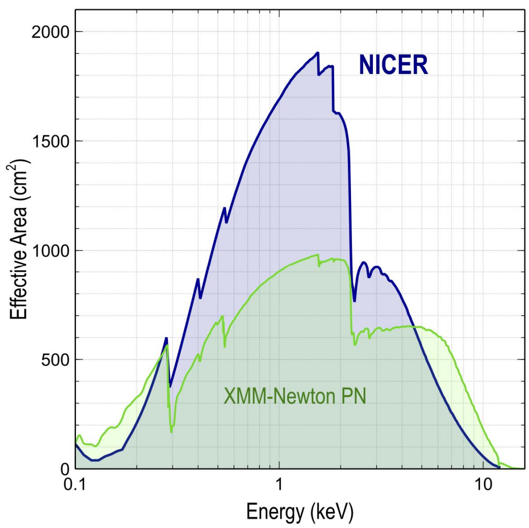

Figure 2. NICER's anticipated effective area as a function of X-ray photon energy, compared to the XMM-*Newton* telescope's timing-capable PN camera. The peak A_{eff} of nearly 1,900 cm^2 exceeds the minimum required with 42% margin.

NICER's long-term pulsar clock stability measurement objective imposes a photon detection time-tagging requirement of 100 ns RMS, with implications for the detector and its readout system, timekeeping on board the payload, and knowledge of NICER's position relative, ultimately, to the Solar System barycenter. A timing error budget (Table 1) breaks down the component contributions. The design choice of a silicon drift detector satisfies the detector allocation, and an on-board GPS receiver satisfies the allocations for absolute time and position uncertainty.

Table 1. The NICER mission's top-level photon time-tagging error budget achieves 100 ns RMS overall uncertainty.

Source	Allocation, RMS (ns)
GPS position	35.0
GPS time reference	55.0
Detector (SDD/FPM) output event timing	70.0
Detector readout (MPU) time-stamping	28.0
Harness cables	7.0
Total (assuming zero correlation)	**100.0**

Finally, to avoid gaps longer than 3 months in the mission-long pulsar clock stability measurements, a Sun-avoidance requirement is also specified: NICER must be capable of accommodating Sun angles as small as 45° from the instrument observing axis.

3. CONCEPT OF OPERATIONS

3.1 Launch and installation on the ISS

NICER is manifested for delivery to the ISS on the 12th SpaceX, Inc., resupply mission using the *Falcon 9* rocket and *Dragon* vehicle. Once the vehicle is berthed to the ISS, installation of NICER proceeds entirely robotically, with no astronaut assistance, in a highly choreographed sequence of operations involving the Space Station Remote Manipulator System (SSRMS "robot arm") and Special Purpose Dexterous Manipulator (SPDM or "Dexter"). Several interruptions of power provision to the payload are anticipated—NICER is designed to survive at least 6 hours un-powered, given sufficient notice for a "preheat" period with sufficient power. Both the *Dragon* vehicle's unpressurized Trunk and temporary staging areas on ISS are able to provide the necessary preheat power prior to robotic transfer steps involving suspension of survival heater operation. Ultimately, NICER is carried to Site 7 (outboard, ram) of ELC2 (ISS zenith; Figure 3), where the payload's Active FRAM is mated to the ELC's Passive FRAM, locked in place, and powered up.

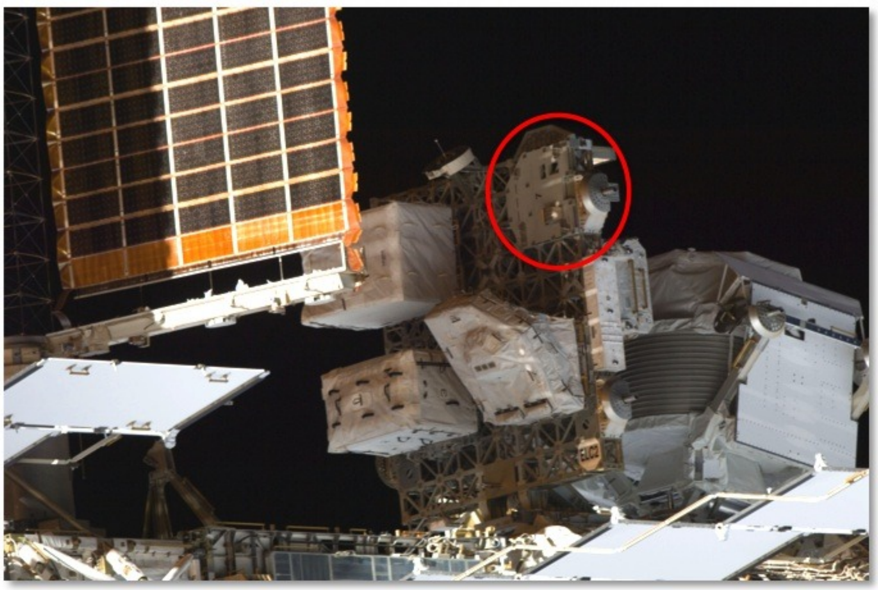

Figure 3. A photo obtained from the ISS robot arm shows Site 7 (circled) on ELC2, the future home of the NICER payload.

3.2 Initial checkout, deployment, and calibration

Initial engineering assessments of the payload's health and safety will include communication with the NICER avionics and verification of nominal communications between the Main Electronics Box (MEB) and other electrical subsystems: the Star Tracker Data Processing Unit (ST-DPU), X-ray detector Measurement/Power Units (MPU), and Gimbal Control Electronics (GCE). The detectors will be activated, before NICER's optics are exposed to the sky, to detect background events. When operators in the SMOC have verified basic commanding and circuit continuity, NICER's one-time-use launch locks—a set of four Frangibolts (TiNi Aerospace, Inc.)—will be fired while under continuous real-time monitoring by the SMOC. Upon confirmation that all launch locks have disengaged, NICER will conduct its first deployment, with motor activations requiring assessment of safety conditions and multiple commands.

The deployment sequence involves 1) activating the latching actuator to unlatch the deployment actuator, 2) rotating the deployment actuator to swing the boom toward the zenith direction, 3) activating the latching actuator to latch the deployment actuator in its deployed configuration, and 4) activating the elevation actuator to rotate the XTI above the ELC so that the star tracker, GPS antennas, and X-ray optics have an unobstructed view of the sky.

Initial calibration will include:

- Verifying GPS solutions for time and position, both on-board and in post-processing on the ground using pseudorange data included in engineering telemetry
- Verifying star tracker performance using quaternions and image frames provided in telemetry
- Verifying star tracker to X-ray observing axis co-alignment by performing scans across bright, compact X-ray sources, such as the Crab Nebula. X-ray countrates in all 56 detectors will be recorded as a function of pointing direction and analyzed to determine empirically the optimum instrument observation axis relative to the star tracker boresight.

3.3 Observing strategy

The NICER science team will maintain a list of targets and update it over the course of the baseline mission; the NICER PI approves the list. This list of targets informs long-range (1–3 months look ahead) planning of NICER observations. On these long timescales, target visibility is dominated by the Sun-avoidance cone (Figure 4) and precession of the ISS orbit plane.

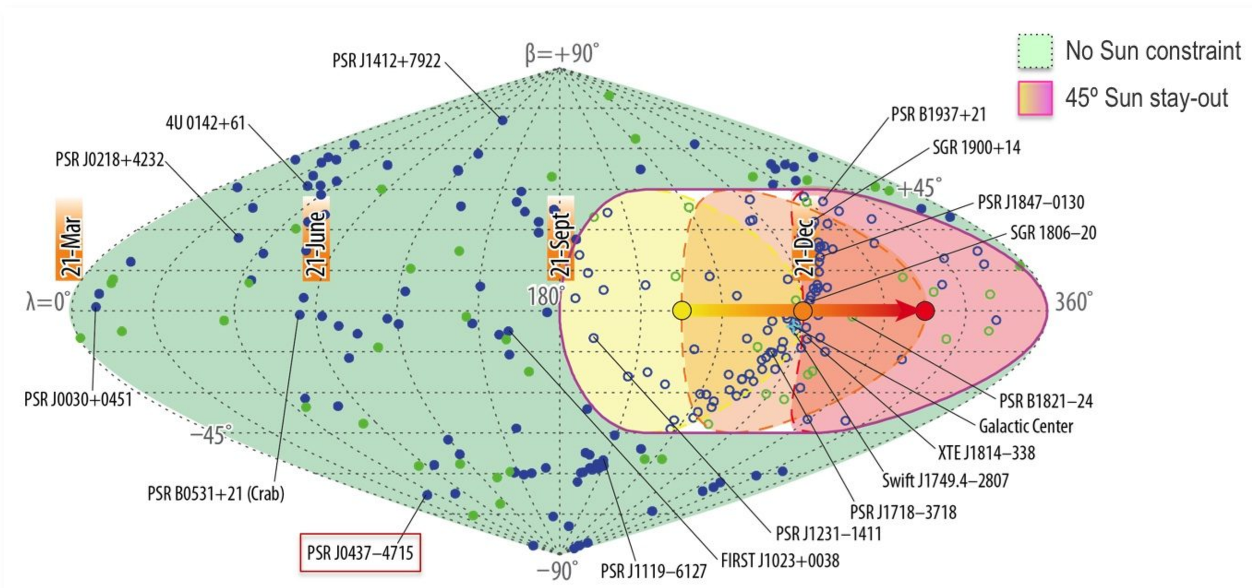

Figure 4. NICER targets are widely distributed across the sky. Plotted in ecliptic coordinates, blue symbols represent 200 known astrophysical targets of interest, including calibration targets, and green symbols simulate 50 randomly distributed targets of opportunity. The path of the Sun over a 3-month period centered on the winter solstice (Dec. 21) is shown by the broad arrow. For a Sun avoidance angle of 45°, exclusion zones at the beginning (yellow), middle (orange), and end (red) of the period are shown by the long dashed borders, while the heavy purple outline encloses the entire region affected by Sun avoidance during these 3 months. Unaffected targets, remaining visible throughout, are shown as filled circles; open circles are targets with restricted visibility. The location of the Galactic Center is shown by a light-blue cross—because of the concentration of targets along the plane of the inner Galaxy, Sun avoidance during the interval depicted here represents the worst-case impact on visibility of the collection of NICER targets.

For the shorter term (days to one week), members of the science team and SMOC staff formulate observing plans guided by science priorities, target visibility, ISS operations (e.g., spacecraft arrival or departure, astronaut extravehicular activity, orbit reboosts, etc.). These plans are typically dominated by NICER's key science targets—millisecond pulsars such as J0437–4715 and J0030+0451—and others that are monitored for long-term variability (such as magnetars) or bursting behavior. Consideration is also given to targets of timely interest, such as accreting binary systems in outburst or in a cooling state following a recent outburst. Finally, monitoring of targets such as the Crab Nebula for calibration and trending also plays a role in routine scheduling.

On a typical day, the NICER SMOC will have multiple opportunities to upload commands to NICER, but in practice uploads will only take place every few days unless interesting transient targets are reported (by other missions or ground-based telescopes) that warrant interrupting NICER's preplanned observing schedule. During regular uploads, timelines of slew commands and tracking target coordinates are sent to the payload. The timelines will be designed to maximize observing efficiency. In a given orbit, NICER will typically observe three celestial targets. The first will be tracked until a viewing constraint (Sun angle, Earth angle, or ISS obstruction) prohibits tracking. NICER will then slew to a new target and track it until a viewing constraint is again encountered. NICER will then slew to the third target and track it for a useful duration. At this point, NICER will again, on the subsequent orbit, be able to track the first target. This process will be repeated until predetermined integrated exposure times have been accumulated. As viewing efficiencies of the original targets degrade, new targets will be woven into the schedule.

Visibility analyses accounting for Sun, Earth, Moon, and ISS structure interference with the X-ray or star-tracker FOVs demonstrate that observing efficiency based on visibility alone is high (approximately 80%), with inefficiencies dominated by time spent slewing between targets. Additional impacts to observing efficiency, such as ISS operations, passages through high-radiation orbital environments, unfavorable thermal environments, etc., are estimated to reduce the overall efficiency of NICER science operations to 54%, well above the minimum required 33%.

Telemetry data

At least 90% of science data collected by the NICER payload is required to be transmitted to and archived on the ground. In practice, data completeness is expected to be much higher. Science data are sent down over an Ethernet connection, in real time whenever the ISS is in contact with the ground via the Tracking and Data Relay Satellite System (TDRSS), about 80% of the time. NICER uses a MIL-STD-1553 serial link for command upload and, if Ethernet is not available, for downlink of housekeeping data (while science data are recorded in onboard memory). The ISS stores data during communication gaps and replays them at the next contact. Data latency is typically much less than 1 hour, and data completeness is typically > 99.5%. If data are lost, the SMOC will request a retransmission from either the POIC, for data that reside within the ISS infrastructure, or from NICER's onboard data recorder.

NICER will downlink buffered science data in CCSDS format ("Level 0"). The SMOC will calibrate and process these data, generating higher-level data products: Level 1 products will be calibrated "event lists" organized by distinct targets. Level 2 products will be event lists screened to exclude poor data. Level 3 files will contain refined information in the form of lightcurves and spectra automatically extracted from the screened event lists.

4. PAYLOAD DESIGN WORK

NICER's Phase B saw significant progress in all areas of the payload's design, including—critically—meeting all ISS Phase 0/1 payload safety requirements.

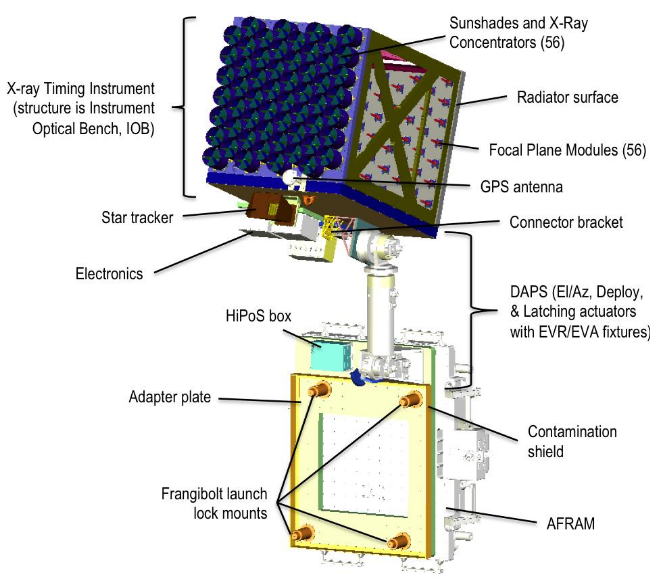

Figure 5. Guided by the star tracker, the NICER payload directs the X-ray Timing Instrument at celestial targets using the gimbaled elevation-over-azimuth (El/Az) actuators of the DAPS system, which is anchored to the active FRAM through the Deploy and Latching actuators. Power to the payload is managed through the High Power Switch (HiPoS) box.

4.1 Mechanical/Structural

In addition to mass and volume constraints imposed by ISS FRAM payload requirements, the mechanical design is driven by launch loads, minimum structural mode frequencies for both launch and disposal, the moment of inertia of the XTI moving mass, and maintenance of co-alignment tolerances across and among the star tracker, X-ray concentrator optics (XRCs), and detectors, during integration and in a wide variety of thermal conditions on orbit. Interfaces between the XTI and other key components such as the FRAM, DAPS, star tracker, electronics boxes, and detector MPUs have been defined. Specific design choices for the launch lock configuration, XRC and detector Focal Plane Module (FPM) structures, and sunshades have been made following extensive analysis. Engineering models of XRC and FPM structures have been fabricated and subjected to performance and vibration testing.

4.2 Pointing

NICER's most complex subsystem is responsible for, among other things, precisely pointing the high mass and moment-of-inertia XTI toward inertial targets, compensating for ISS orbital motion at the 1 arcmin level in the presence of ISS vibration-induced jitter and other disturbances such as stepper-motor-induced jitter, harmonic drive imperfections, and control loop limitations. The Deploy and Pointing System (DAPS) has key mechanical, electrical, thermal, and flight software interfaces with the XTI and the FRAM; importantly, it enables re-stowing of the XTI into a compact configuration similar to that at launch, to eliminate any potential impact NICER might otherwise have on ISS operations. Significant analysis has informed the definition of performance specifications for actuator hardware, control electronics, star tracker, and pointing flight software. Testing with a variety of engineering models is in progress.

The NICER DAPS hardware is supplied by Moog, Inc. (Chatsworth Operations). NICER's star tracker, the Micro Advanced Stellar Compass, including a suitable baffle, is supplied by the Technical University of Denmark.

4.3 Electrical

The generous power accommodation for ISS ELC payloads simplifies NICER's electrical design (in some instances, at the expense of complicating the thermal design). Changes to earlier electrical architecture resulting from ISS requirements include grounding modifications to isolate returns from ISS structure, and the design of a high-power switching capability to manage power from the ELC.

NICER's Main Electronics Box—which provides the flight command and data-handling avionics, the GPS receiver and processor, and power distribution—as well as its Gimbal Control Electronics are supplied by Moog, Inc. (Broad Reach).

4.4 Thermal

Storage of thermal energy to maintain electronics within survival temperature limits during extended (up to 6-hour) power-off periods is a significant design driver, necessitating phase-change material integrated into the electronics deck structure. Mitigating temperature gradients across the Integrated Optical Bench to minimize thermal-mechanical distortions of the aluminum structure, a key component in NICER's pointing budget, is accomplished through software-controlled heaters on the optics and detector plates. Thermal hardware, blanketing, and coating configurations are based on analysis across the wide range of ISS orbit beta angles and multiple realistic target tracking sequences to model solar illumination on the XTI.

4.5 X-ray Optics

Exploiting the fact that imaging is not required, NICER's single-reflection X-ray concentrators represent a simplification of high-heritage grazing-incidence optics, one that yields a significant increase in efficiency over traditional arrangements that involve two (primary and secondary mirror) reflections. Another novel aspect of NICER's optical design is the parabolic figure imparted to the replicated, gold-coated aluminum foils, to optimize the encircled-energy function of the XRCs. Several engineering model XRCs have been assembled and tested for performance, meeting or surpassing requirements before and after environmental testing including vibration (see Balsamo et al., this volume).

4.6 X-ray Detectors

Analog and digital detector readout electronics yield both unprecedented time-stamping of X-ray photon detection events and near-optimum energy measurements for silicon detectors. A novel two-channel readout approach also offers discrimination of photons that interact far from a detector's center, providing a means of distinguishing between cosmic X-rays focused by the optics and radiation background events. MIT and Noqsi Aerospace, Inc., provide the FPM/MPU subsystem, integrated with modestly customized silicon-drift detectors supplied by Amptek, Inc.

4.7 SEXTANT

NICER's X-ray timing instrument and operations concept provide an ideal platform for the SEXTANT demonstration of pulsar-based spacecraft navigation (XNAV). The SEXTANT team, funded by NASA's Space Technology Mission Directorate, is developing an augmentation to the NICER flight software that will process photon events on-board, and expects to extract a one- to ten-kilometer orbit solution in real time.

Testing of the SEXTANT system, to begin in the second half of 2014, will use GSFC's XNAV laboratory testbed pulsar simulator to provide X-ray stimulus to the NICER XTI, modulated to appear as though the payload were already in orbit observing a sequence of millisecond pulsars.

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